Contents

Appendix B: Decision Model Comments

Comment	Consensus	Reviewer	Done
3. Pg B-3, Existing versus new wells general: In general, available data outlined on page B-4 is not available for existing wells as a lot of the geologic, hydrologic and geosciences data can only be obtained when the well is drilled or completed. In addition, most existing wells will not have seismic data to locate faults in area and if it is available it will most likely be 2D seismic which has poor resolution and rarely 3D seismic data. If the 3D seismic data is available, the 3D seismic data might not be deep enough to map the basement faults because the target of the 3D seismic data is the hydrocarbon producing zone which is typically above the injection zone.	Seems to miss the point – does text need a tweak? ??? If most injection disposal wells are converted from other usages, would some of the data be available from the state regulatory offices (including some non oil/gas agencies)? Okay w possible clarification	**Jeff Bull** *Oil/Gas Industry*	Already covered (B-3 and 4), change to Clarify category
5. Pg B-3, prgh 5, ln 7-9: The proximity to the basement is not as critical as proximity to a critically stressed, favorably oriented fault. (See Basic Mechanism of Injection Induced Seismicity – comment 2). If there is no fault in area or no critically stressed favorably oriented fault in the basement area, one can successfully operate an injection well injecting into or near the basement	Don't entirely agree - tweak or clarification? More discussion on basement	Jeff Bull Oil/Gas Industry	As stated (p B-3), basement rock may be an additional consideration.

Appendix D: Petroleum Engineering Comments

Comment	Consensus	Reviewer	Done
2. While the analysis techniques do not provide a unique (or even necessary and/or sufficient) indicator for apriori predictions to identify if seismicity may be induced from a specific injection operation; the techniques may yield useful insights when evaluating, on a "post-mortem" basis, whether injection operations may have departed from ideal radial flow and potentially reached a less permeable fault boundary (and hence could have contributed to the subsurface stress perturbation of sufficient size to induce fault slip). a. The lack of solution uniqueness and the inherent range of uncertainties in reservoir and bottomhole pressure measurements, coupled to the extended time duration needed to observe trends, limit the practical extent that the methods may be applied in managing risk of induced seismicity. The analytical techniques should be viewed in the context that they provide one more tool available in the assessment "toolkit"; but are not reliable for use as "early warning" systems; as many other subsurface factors may be present that lead to departure of pressure behavior from ideal radial flow conditions. b. These point should be better emphasized in the main body of the report in the Section "Petroleum Engineering Applications for Evaluating Induced Seismicity" and also in Appendix D.	Until run, unknown, it is a tool 'a' disagree, operating data is a program requirement b) look at	**Kris Nygaard** *Oil/Gas Industry*	Inserted sentence in lead paragraph (p D-2) Edited intro (p D-3)
3. Appendix D, Figure 10 I do not think that plotting station number as a variable on this plot effectively conveys how seismicity rate may change with station coverage.	Discuss:	**Heather Savage** *Academic Laboratory*	Comment inserted with graph. Address other (a-f) comments in Geoscience

Appendix C: Geosciences Comments

Comment	Consensus	Reviewer	Done
5.6 Errors in Scientific Descriptions (continued) 1. The "Seismic Risk" section of Appendix C says the following: "Seismic surface waves are the most likely to be felt, having the greatest amplitude and a motion similar to ocean waves. For the most damaging	Context?	**Robin McGuire** *Consultant*	Need to Research issue: see suggested changes

earthquakes, the earth moves very similar to the surface of the ocean in a storm." This is only true at large distances (>50 km) from the causative fault. Near the fault, body waves have larger amplitudes, are more likely to be felt, and are more damaging. I would remove the focus on surface waves.			
5.7 Unclear Descriptions 1. The "Basic Seismology" section of Appendix C (page C-5) says the following: "An earthquake (seismic event) occurs when there is brittle failure along a fault at depth. The resulting brittle failure of the fault results in slip or displacement that generates elastic waves that propagate away from the fault. The event can be from a source in, on, or above ground that creates a wave motion in the earth." a) It appears that the discussion is mixing up seismic waves generated by earthquakes, with man-made seismic waves used to create images of what lies underground. As such, the description of earthquakes and seismic waves is muddled. b) Earthquakes generally occur on pre-existing faults, and there is no brittle failure of intact rock. (An exception is during hydraulic fracturing, which is designed to fracture intact rock.) Thus brittle failure does not cause fault slip; fault slip causes strain energy to be released in the form of seismic waves. If "brittle failure" is used as a synonym for fault slip, that is not standard in seismology, and is not consistent with the above quote, which says that one causes the other.	Both create seismic waves as do explosions at or above the earth, see references. Clarify discussion of energy waves, i.e. recorded and therefore requiring separation from earthquake results Verify 'b'	**Robin McGuire** *Consultant*	a) See proposed changes b) See proposed changes Basic rock mechanics: brittle failure, ditto geophysics with brittle crust Earthquakes can create new faults, though most occur on preexisting ones.
1. Appendix C, Pg. 2 Both faults and joints have movement, joints do not have shear movement.	Verify correct definition	**Heather Savage** *Academic Laboratory*	See proposed change Both faults and joints have separation, only faults have offset.
2. Appendix C, Pg. 5 Shale is not always ductile. When shale is hydrofractured to release natural gas, this is a brittle process. They are certainly more brittle than the unconsolidated sediments discussed in the following paragraph. I do not think there should be a distinction of which rock type is easier to induce earthquakes.	context	**Heather Savage** *Academic Laboratory*	clarified para: C-5
3. Appendix C, Pg. 5 "Earth stress reaction" is an awkward phrase. I think "Crustal deformation" might be better.	discuss	**Heather Savage** *Academic Laboratory*	Revised word: C-5

4. Appendix C, Pg.5 The USGS Quaternary fault map does not seem particularly relevant to the induced seismicity problem. Specifically, most of the induced seismicity we have seen in the past few years occurs on ancient faults that would never have appeared on these maps. Indeed, some of the faults that have been activated did not appear on any map. As is stated in the document, the Quaternary fault map only includes faults that have hosted earthquakes above a M6, which is also irrelevant to induced seismicity we've seen to date.	Same comment under B page 2. True, but still a concern for location	**Heather Savage** *Academic Laboratory*	CLARIFY Locating a disposal well on top of a known Quaternary fault is not a good idea.
3. C-6 Basic Seismology It should be noted that the surface shaking associated with seismic waves is also a function of the hardness of the rock near the surface.	Tweak?	**Heather Savage** *Academic Laboratory*	CLARIFY Rock Mechanics C-4-5 discusses rock rigidity and variations in compaction. Specific use of the term hardness is not needed for this report. Also top of p C-9, covers variation of local surface geology.

3. Appendix D, Figure a) For instance, how does the number of stations in the time around January 10 vary so dramatically? b) Was station coverage really changing that significantly on a weekly or monthly basis? c) Why are those points so close together? d) I think a more effective plot to make to deal with the issue of seismicity rate change with station coverage is to plot all of the events with magnitude on the y-axis and time on the x-axis (this is often referred to as a stick plot). Number of seismometers over time can be displayed along to x-axis. Although changes in station coverage is of course a concern when considering seismicity rates, the most profound change when additional stations are installed is the number of small events that are recorded. e) If there are much more numerous small events when there are more stations, then some correction may be needed. In order to account for this, the magnitude of completeness should be calculated. This is the minimum magnitude for which there is confidence that all of the earthquakes have been reported, usually by plotting the Gutenberg-Richter distribution. Once that minimum magnitude of completeness is determined at the time when the fewest stations existed, this should be the cutoff to compare seismicity at all time periods. f) If seismicity rate still increases with time, it is due to an actual increase in seismicity.	The G-R distribution is outside the scope, but if a simple, practical method for calculating rate change exists, it would be helpful. Not an easy change	**Heather Savage** *Academic Laboratory*	CLARIFY a-c) Actual station additions were plotted, so yes it changed that drastically as researchers rushed to investigate the source. d) Timeline plots: x = time y = magnitude secondary y = stations GROUP e) outside the scope f) can't stand alone—related to analysis outside scope

Appendix E: North Texas Cases Comments

Comment	Consensus	Reviewer	Done
5.1 Case Study Selection 1. I think there is a glaring oversight in this document in terms of the case studies that were chosen. The case studies discussed are the most clear-cut cases of induced seismicity in the last few years. The seismicity began shortly after the disposal well began pumping, earthquakes were located in space and associated with a single, specific well, and in some cases operators shut down pumping and earthquakes began to tail off. These were the easiest cases to deal with in some sense. The more difficult situations are the ones that are less clear cut but still extremely compelling as examples of induced seismicity, such as Prague, Oklahoma, Trinidad, Colorado, and Snyder, Texas. In these cases, the onset of pumping and the onset of seismicity were offset by long time periods, some times years. Still, the uptick in seismicity indicates that non-natural events are occurring.	Selection was covered in intro. Expand? Timing: prague was later, Trinidad was in M, Snyder was intermittent and recent	**Heather Savage** *Academic Laboratory*	Already covered in main body (p 13 at bottom)

4.6 North Texas Cases 1. It seems as though the earthquakes mentioned in the DFW case study all occurred in the sedimentary rocks? This is in line with my earlier comments regarding that faults do not have to be hosted within basement rocks to have earthquakes.	Check text, but do not think we said it had to be in basement, just a correlation with deep basement faults seen	**Heather Savage** *Academic Laboratory*	Added a word to the Main Document background (p 6)
3. There needs to be a clearer description of what was learned from the various pumping tests performed. Which wells showed anomalies? Where are they in reference to the earthquakes? All of this information is in there, but it is not presented in a way that is clear to the reader.	Re conclusions	**Heather Savage** *Academic Laboratory*	? brief summary of analysis or not before actions taken
1. E-8 ~~Additional Geoscience Information~~ There will be some doubts that the 2013 and 5/15/09 events were related to the injection because of the significant depth of the hypocenters reported. As such, it would have been useful for this to have been noted.	Re conclusions	**Ed Steele** *Oil/Gas Industry and Consultant*	See note with Table E-3
2. E-20 North Texas Area Lessons Learned Fifth bullet – What is meant by many areas? a. Just the presence of additional monitoring stations does not guarantee that active faults will be found. Additional monitoring stations may be warranted when there is some indication of previously unreported seismic activity.	Check context and rework?	**Ed Steele** *Oil/Gas Industry and Consultant*	

Appendix F: Arkansas Case Comments

Comment	Consensus	Reviewer	Done
2. Appendix F, Pg.7 There are some question marks at one of the bullets where a figure number should be.	Easy fix	**Heather Savage** *Academic Laboratory*	Fixed (F-28)
2. F-16 Figure F-2 It is unclear that any disposal into the Kissinger, Brown or SRE wells may have reached the basement rock and contributed to induced seismicity. As they are shown on the same figure, this may leave the casual reader with the impression that it is clear that they did so when it is believed that no confirmation of such is provided.	Clarify context. The fault clearly goes to basement, and the injection zones touch the upper reaches of the fault.	**Ed Steele** *Oil/Gas Industry and Consultant*	The communication potential is discussed in paragrapy 2 under Geologic Setting on p. F-2
3. F-17 Figure F-3 While it is understood that this figure was pulled from a publication, there is no correlation provided as to how Well #1 or Well #5 relate to the wells shown on the other figures. Without context or other correlation, this would likely be confusing to many readers as to what wells are shown here as no other mention of these particular wells could be found.	Clarify or replace	**Ed Steele** *Oil/Gas Industry and Consultant*	Well names added to figures F-3 and F-7

Appendix G: Braxton Case Comments

Comment	Consensus	Reviewer	Done
1. Appendix G and other places: The text on the geologic maps and cross-sections are generally too small to read.	Verify	**Heather Savage** *Academic Laboratory*	

Main Report Comments

Comment	Consensus	Reviewer	Done
5. Pg ES-2, prgh 2, footnote 5: The definition of faults of concern needs to be more specific with regard to "significant earthquake" (see Variety and Validity of Approaches – comment 2). The definition also needs to include an expansion of the term "optimally orientated" to include a fault whose orientation is such that the direction of the principal insitu stress is at a 30-50 degree angle to the fault plane. The definition also needs to include a statement that the fault must be critically stressed meaning that there is sufficient stored energy (stress) that should the fault slip, it would generate a seismic event of sufficient magnitude to be detected.	We should likely point to variability in regional geology as the need to stay less prescriptive. Good in doc, regional geo issue Also in Exec Summary	**Jeff Bull** *Oil/Gas Industry*	
1. Pg 2, prgh 3, ln 7: I agree with the statement but more specifically, hydraulic fracturing has the potential to create felt events at the surface when the stage being fractured transects a fault such as what occurred during the Horn Valley, BC, Cuadrilla, UK, or recent eastern Ohio events. a. Note that in footnote 12 called out in the line referenced above, you have definition of a fault of concern. This definition is different than the one listed on Pg ES-2, footnote 5. The footnote 12 definition is more complete and should be used throughout the report.	the footnotes main difference is the text about the fault length in FN12	**Jeff Bull** *Oil/Gas Industry*	
2. Pg 8, prgh 4, ln 5-7: The statement is not accurate. Petroleum engineering methods focus on an existing pressure within a vast area (40-160 acres based upon allowable well spacing) that "pushes" the product (gas or liquid) into a well and as product is removed the pressure will dissipate over time. An injection well operates in the reverse with the highest pressure at the well that dissipates as the pore pressure radiates out form the well. See Basic Mechanism of Injection Induced Seismicity – comments 3 and 4.	Context? Tweak or respond Is he saying that the application of petroleum engineering tools and methods are inappropriate? If so, we need to answer him. The application of petroleum approaches is one of the major findings and recommendations.	**Jeff Bull** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
3. Pg 8, prgh 4, ln 10-12: The statement is not totally accurate as it is the pore pressure that radiates out from a well that interacts with the well. Yes there is a potential that the liquid may reach a fault but the liquid does not grease the existing fault and cause it to slip. The pore pressure disrupts the insitu stress field that is holding the fault together and causes it to slip. a. The statement regarding "unknown distance" is critical when considering how far the pore pressure will travel. And as it travels, the pore pressure is dissipated, so knowing the distance and perturbation of pore pressure is important. Note that understanding the perturbation of the pore pressure requires very specific data that is rarely known and has to be estimated and sophisticated modeling that is very expensive ($50-150,000/well)	Context? Tweak or respond Probably need to clarify our language	**Jeff Bull** *Oil/Gas Industry*	
4. Pg 10, prgh 1, ln 2-3: You need to define the term "static pressure". In petroleum reservoir terms, static pressure is the natural pressure within the formation (i.e. formation pressure). The injection pressure is the pressure it takes to push the fluid down the bore hole and out into the formation. A comparison of static pressure to injection pressure is representative of the pore pressure at the bore hole that then radiates out from the bore hole and dissipates with distance. During normal operation of a disposal, should the injection pump be turned off, the injection pressure would bleed off over time back down to the static or formation pressure. The rate of the bleed off is based upon the hydrogeological characteristics of the formation into which one is injecting.	Target audience Add to terminology?	**Jeff Bull** *Oil/Gas Industry*	
5. Pg 12, prgh 4, bullet 2: The statement regarding exceedance of the theoretical friction threshold implies that the injection water lubricates the surfaces between the 2 sides of the fault allowing one side to slip along the other side. As presented in Basic Mechanism of Injection Induced Seismicity – comment 1, the primary mechanism is the disruption of the insitu stresses holding the fault together by pore pressure radiating our from the point of injection.	Look at wording	**Jeff Bull** *Oil/Gas Industry*	
Errors in Scientific Descriptions 1. The section labeled "Geologic Stress Considerations," page 6, says that "…a principle (sic) stress direction exists…" and goes on to talk about the orientation of faults with respect to the "…the principal stress direction." This section is an erroneous condensation of parts of Appendix M, which describes "…three principal stresses that are oriented perpendicular to one another." In fact it is the orientation of faults with respect to the orientation of the three principal	Look at text Revise accordingly Also in Exec Summary	**Robin McGuire** *Consultant*	

Comment	Consensus	Reviewer	Done
stresses that is important. This concept is not accurately stated on page 6.			
3. It's unclear what group actually wrote this Report. Page 3 defines the NTW (National Technical Workgroup of EPA) and the WG (the Induced Seismicity Working Group, some of whom are outside of EPA), and the WG members are listed on page 31. The Executive Summary indicates that the NTW is taking credit for the Report, but page 5 has sections titled "Working Group Tasks" and "Working Group Approach" that gives the WG strategy to develop the Report. The WG and/or the NTW should determine how to handle this administratively.	Covered in discussion of NTW and working group Could we change working group to writing group? That would distinguish it from the Workgroup.	**Robin McGuire** *Consultant*	
7. The entire Report needs a detailed scrubbing by a technical editor. There are problems in verbiage, consistency, and grammar on every page, to the extent that this version should be considered a "rough draft." (not inc. here)	If funding is available, yes	**Robin McGuire** *Consultant*	
9. The "Technical Recommendations…" document in Appendix A says that output of the study should include "Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations." Such a comparison is missing (unless I overlooked it).	Verify Isn't part of the issue that since state UIC programs differ widely in their regulatory requirements, it would be difficult to create such a comparison? Therefore we outlined technical inputs that would be most helpful for the program director to "consider" in his/her management.	**Robin McGuire** *Consultant*	
10. The "Technical Recommendations…" document in Appendix A says that output of the study should include "Recommended measurement or monitoring techniques for higher risk areas." These measurement or monitoring techniques are described in general terms such as injection well operational characteristics, or seismic monitoring arrays, for any well where induced seismicity is a concern. No special recommendations are given for "higher risk areas."	Verify Doesn't the decision model include incidences of when the concern could be resolved by additional information gathering, operational constraints, etc.?	**Robin McGuire** *Consultant*	
11. The "Decision Model" section of the Report (page 22+) says that the decision model addresses 3 scenarios involving disposal wells and seismicity. However, it does not mention an important case: a new disposal well that is proposed in a region that is experiencing seismicity, possibly related to existing wells. Does the decision model cover that case? If not, how should the Director make a decision for such a proposed well?	Verify I thought the top of the model would have covered this scenario. History of injection without success?	**Robin McGuire** *Consultant*	

Comment	Consensus	Reviewer	Done
5.7 Unclear Descriptions (cont) 1. The "Research Needs" section uses the following terms in 3 paragraphs (page 27): ▪ Injection well operating data ▪ Operating well behavior ▪ Injection well operational characteristics ▪ Disposal well operational behavior ▪ Disposal wells operating parameters Do these terms mean the same thing, or are there subtle, unexplained differences? The reader is left muddled.	Clarify in document	**Robin McGuire** *Consultant*	
13. The section titled "Petroleum Engineering Applications…" (page 8) introduces the phrase "Hall integral and derivative responses" but does not explain what this is. Appendix D, "Petroleum Engineering Considerations," explains the Hall integral (page D-9) as "…a numerical integration between the operating BHP and static (reservoir) BHP." Why is an equation not given? Bullets on pages D-9 and D-10 indicate the Hall integral is the "cumulative (ΔP*ΔT) function" and the Hall integral derivative as the "difference between successive Hall integral values," divided by the "difference between successive cumulative injection values." Yet if I look at Figure D-4 showing the "Hall integral with derivative", applying the above definitions, I calculate an average derivative value of 0.12, not values of zero to 60,000 as shown on the plot. Obviously I am missing something, and other readers will be muddled as well.	Verify, and add response	**Robin McGuire** *Consultant*	
1. I have other minor corrections or comments on the report text, which I can send as an annotated pdf copy with comments as inserted pdf sticky notes. An annotated copy is available in the Peer Review Record.	Verify or leave to tech editor Covered in contractor's summary?	**Craig Nicholson** *Academia*	
2. My concerns about the report generally fall into 3 categories: 1) incomplete or inadequate acknowledgment of previous studies and EPA reports on this very topic that provide similar recommendations, criteria or practical approaches to help minimize the potential of injection induced seismicity;	Verify reference on first point On second point other authors disagree Third point is covered	**Craig Nicholson** *Academia*	
5.2 Previous Studies (last) 5. Other more up-to-date references are listed under Charge Question 4 that would also be useful to incorporate. I also found it somewhat misleading to make statements like: "The review of injection-induced seismicity literature revealed a lack of a multi-disciplinary approach inclusive of petroleum engineering techniques" (page 8, 2nd para). a) Several studies on injection induced seismicity are quite multidisciplinary, and although they may not use the entire suite of reservoir engineering techniques proposed in this report, they do investigate injection	Verify	**Craig Nicholson** *Academia*	

Comment	Consensus	Reviewer	Done
pressure-time histories and volumes, reservoir characteristics, subsurface geology defined by exploratory test wells, inferred pore pressure changes at a distance from disposal operations, historical and recent seismicity and even the pressure fluctuation response in shallow wells as a result of adjacent seismic activity [e.g, Nicholson et al., Bull. Seismo. Soc. Am., 1988]. Many of these techniques are also used by the petroleum industry to characterize the hydrogeologic response of reservoirs.			
1. In performing my peer review, I considered the charge questions and the project framing around 6 key objectives (as described on page 5 of the report): • Identifying the parameters that are most relevant to screen for injection-induced seismicity; • Identifying siting, operating, or other technical parameters that are collected under current regulations; • Identifying measurement tools or databases that are available that may screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity; • Identifying other information that would be useful for enhancing a decision making model; • Identifying screening or monitoring approaches which are considered the most practical and feasible for evaluating significant injection-induced seismicity; and • Identifying lessons that have been learned from evaluating case histories. Based on the information as summarized in the main body and appendices of the report, Objectives (2) and (6) appear to have been addressed. However, Objectives (1), (3), (4), and (5) do not appear to be clearly and/or effectively addressed in the report. … Adding a section that clearly provides specific summary "answers" to each of the six "project objectives questions" would substantially improve clarity of communication. Alternatively, the "Report Findings" section on page 30 could be revised to specifically address each of the project objective questions.	Add summary	**Kris Nygaard** *Oil/Gas Industry*	
2. While the analysis techniques do not provide a unique (or even necessary and/or sufficient) indicator for apriori predictions to identify if seismicity may be induced from a specific injection operation; the techniques may yield useful insights when evaluating, on a "post-mortem" basis, whether injection operations may have departed from ideal radial flow and potentially reached a less permeable fault boundary (and hence could have contributed to the subsurface stress perturbation of sufficient size to induce fault slip).	Until run, unknown, it is a tool 'a' disagree, operating data is a program requirement b) look at	**Kris Nygaard** *Oil/Gas Industry*	Inserted sentence in lead paragraph (p D-2)

Comment	Consensus	Reviewer	Done
a. The lack of solution uniqueness and the inherent range of uncertainties in reservoir and bottomhole pressure measurements, coupled to the extended time duration needed to observe trends, limit the practical extent that the methods may be applied in managing risk of induced seismicity. The analytical techniques should be viewed in the context that they provide one more tool available in the assessment "toolkit"; but are not reliable for use as "early warning" systems; as many other subsurface factors may be present that lead to departure of pressure behavior from ideal radial flow conditions. b. These point should be better emphasized in the main body of the report in the Section "Petroleum Engineering Applications for Evaluating Induced Seismicity" and also in Appendix D.			Edited intro (p D-3) Main doc?
3. The description of a "fault of concern" is problematic from both a scientific standpoint, as well as clarity of communication in the report. From a scientific standpoint, a measure of earthquake size and energy release is the static (or scalar) seismic moment (Mo). The calculation of this quantity is straightforward in terms of the equation Mo = μ D S, where μ is the shear modulus, D is the average displacement along the fault, and S is the surface area of the fault; hence fault length is only one piece of the overall factors defining the energy release. Secondly, it will be hard for the average reader to efficiently comprehend the current definitions as these are located in different places through-out the report. A single, more precise definition, for "fault of concern" could be provided by the following definition below, and could be listed in the definition of terms section. a) …. p. 28 of the report considering the key geologic and engineering factors. This section of the report could be strengthened to better emphasize the risk is associated with "faults of concern" and not "small faults" or stable faults. This shortcoming could be effectively "A fault of concern is defined, for the purpose of this report, as a fault optimally oriented for movement and located in a critically stressed region, is of sufficient size, and possesses sufficient accumulated stress / strain, such that fault slip and movement has the potential to cause a significant earthquake (where a significant earthquake is defined for this report as of such magnitude to potentially cause damage or endanger underground sources of drinking water)"	not a practical comment for UIC program application FOC will be revisited	**Kris Nygaard** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
6. Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions. (1) the presence of a fault of concern(a); (2) a subsurface pathway for hydraulic communication from the disposal well to the fault of concern; and (3) a sufficient subsurface stress perturbation primarily induced by the disposal activities, in sufficiently close proximity to a fault of concern, such that the resulting stress perturbations cause the fault of concern to slip. Footnote: (a) "A fault of concern is defined for the purpose of this report as a fault optimally oriented for movement and located in a critically stressed region, is of sufficient size, and possesses sufficient accumulated stress / strain, such that fault slip and movement has the potential to cause a significant earthquake (where a significant earthquake is defined for this report as of such magnitude to potentially cause damage or endanger underground sources of drinking water)	revisit some of our wording possibly, but not sure much is gained	**Kris Nygaard** *Oil/Gas Industry*	
9. Page 13, Determination of Injection Induced Seismicity Suggest revising the sentence "Although these approaches are qualitative and do not result in proof of injection-induced seismicity, they may be useful to UIC regulators. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for taking early prudent action to address the possibility of induced seismicity." to further clarify the limits for use of temporal and spatial correlation. The sentence would be better restated as "Although these approaches are qualitative and do not result in positive proof of injection-induced seismicity, they may be useful to UIC regulators as preliminary screening tools to identify the possibility of injection induced seismicity. Evaluating causality requires evaluation of all important natural and anthropogenic triggers that can perturb the subsurface stress regimes in proximity to faults in the local area. As such, proof of induced seismicity is difficult to achieve and may be time-consuming, but is not a prerequisite for taking early prudent action to address the possibility of injection induced seismicity."	Discuss	**Kris Nygaard** *Oil/Gas Industry*	
10. Page 15, N. Texas Area Suggest revising the sentence "Since the two wells were shut-in the frequency of seismic events in the immediate focus area has substantially decreased" as this is contradictory to information contained in the Janská, E., Eisner, L. 2012 publication that that suggests seismicity continued for an extended time period in proximity to one well after shut-in (when considering the DFW airport measurements). Reference available online at the link:	The continuation is outside the immediate area – verify write-up	**Kris Nygaard** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
Janská, E., Eisner, L. (2012): Ongoing seismicity in the Dallas-Fort Worth area, The Leading Edge, 31 (12), 1462–1468.			
11. Page 21, Lessons Learned Suggest revising the sentence "Increased seismic monitoring stations may be warranted in many areas to pinpoint active fault locations and increase detection of smaller events" to avoid appearance of making policy recommendations in this section. The lesson learned is better restated as "In the case studies, regional monitoring was insufficient to pinpoint active fault locations and detect smaller events; and more sensitive monitoring systems were required to accurately identify the fault".	Check context Might have a point on the policy issue	**Kris Nygaard** *Oil/Gas Industry*	
12.Page 22, Decision Model Suggest revising the sentence "(1) pressure buildup from disposal activities, (2) faults of concern, and (3) a pathway for the increased pressure to communicate with the fault" to provide more precise definition of terms as discussed in the response to charge questions.	Check context	**Kris Nygaard** *Oil/Gas Industry*	
13. Page 26, Research Needs Suggest revising the sentence "For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics; seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance" to also explicitly state "geomechanics".	Look at but keep to higher level grouping	**Kris Nygaard** *Oil/Gas Industry*	
14.Page 27, Research Needs The discussion related to "Future research is needed to explore the correlation between disposal well operational behavior and earthquake events. The research should consider interaction between offset disposal wells on the operational plot characteristics along with area geology (flow geometry related to karstic vs. fractured carbonate)" is very problematic that this would tend to imply to the reader that simple analytic tools can be used to evaluate correlation between the disposal well operational behavior and earthquake events. From a practical view, this is simply not the case and analytic models can not represent the complex physics of the problem. Understanding correlations between disposal well operational behavior and earthquake events requires coupled geomechanics-reservoir modeling, accounting for subsurface complexity and the natural tectonic environment. If the intent was for research to explore if simple analytic models can be used as a possible proxy for advanced coupled geomechanics-reservoir modeling and better define the limits of the applicability for simple analytic model use, then this could be a viable research objective. This discussion should be reworded to more effectively describe the intended scope and specific research deliverable(s) for this proposed research need.	Clarify report Last phrase is beyond Scope	**Kris Nygaard** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
15. Page 29, Management Approach The sentence "Take action earlier to minimize the potential for additional injection-induced seismicity rather than requiring substantial proof of the causal relationship" reads as a recommendation and is not sufficiently descriptive. Further many stakeholders, when reading this statement, will be concerned that this statement provides a recommendation for judgment that is not grounded in reasonable consideration of facts. This sentence could be restated to better reflect actual management approaches as understood from the case studies. A statement that better reflects the case study approaches would be framed around the following: "When surface felt seismic events unexpectedly occur, regulators are immediately called on by the public to quickly respond to identify the "cause" of the felt seismicity and to "take action" to reduce the likelihood of future seismic events. However there is a significant difference in the resources, skills, time, and effort required to locate seismic events versus actually determining causation. Sound science and spatial / temporal correlations should both be considered when responding to public concerns and taking action earlier to minimize the potential for additional injection-induced seismicity (rather than requiring substantial proof of the causal relationship).	Review context	**Kris Nygaard** *Oil/Gas Industry*	
17. Page 34, Terms a) The table that describes Magnitude versus Earthquake Effects should be revised or supplemented to include ground shaking characterization and examples for different local regions how magnitude value may be related to ground shaking, by considering PGA, PGV, or Modified Mercalli Scale. This can be accomplished by referencing USGS information readily available: … b) Should include terms definitions for "Hypocenter", "Modified Mercalli Scale". Peak Ground Acceleration, Peak Ground Velocity. c) Revise the definition of "Fault of Concern" based on comments provided in response to charge questions. d) Revise definition of "Magnitude" to clearly state that this characterizes the energy release at the hypocenter, and is not direct measure of ground shaking, as actual ground shaking is a function of energy release, distance from hypocenter, and local geologic/soil conditions.	a) Out of Scope b) Verify c)Covered above (will discuss) d) Verify	**Kris Nygaard** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
b) Second, in order to determine whether a fault is optimally oriented to the stress field, the frictional strength of the fault must be assumed. The main paper on this issue cited in this document (Holland 2013), assumed that faults have a frictional strength of 0.6 (this is never stated clearly, but the Hurd and Zoback (2012) paper that Holland references does assume this). It should be made clear that this, in many cases is a complete assumption. Townend and Zoback (2000) demonstrate that some mid-continent faults have friction values close to 0.6, but this should not be assumed in all cases. Although the coefficient of friction of bare rock surfaces is typically this high, faults often have granular gouge layers (from abrasion) that are rich in clays, and have a coefficient of friction closer to 0.3-0.4. Hurd and Zoback (2012) argue that faults in the midcontinent do not have gouge zones, but at least through my own personal experience in the field, I would say that is not usually the case. The presence of clays and weakening of faults changes the range of angles a fault can be from the maximum stress direction and still slip. For instance, the San Andreas fault is oriented almost 90 degrees from the maximum horizontal stress, meaning that it should essentially be pinned (Zoback et al. 1987). Although this is an extreme example, it highlights the uncertainty involved in assigning "faults of interest" based on orientation of the fault to the remote stress field. To highlight this point, I will mention that Holland (2013) suggests that faults in Oklahoma that are oriented east-west are unlikely to host earthquakes, despite the fact that a M5 earthquake occurred on an east-west striking fault as part of the 2011 Prague sequence (Keranen et al. 2013). Although this earthquake may have been pushed to failure by other nearby faults at orientations that would classify them as "faults of interest", the complexity of fault interaction suggests that limiting the scope of investigation to faults at a certain angle may be problematic. A full characterization of all faults in the vicinity of a well seems more appropriate.	b) clarify FOC as above	**Heather Savage** *Academic Laboratory*	

Comment	Consensus	Reviewer	Done
c) The other consideration that could be addressed more specifically in this document is that absolute stress levels on faults at any time is unknown, so it is never clear what pressures will be the "tipping point" that causes failure. Time-dependent fault processes, specifically time-dependent frictional properties, should be addressed more in the future as well. Although this is an area of active research, this document would be remiss if it did not at least mention that understanding the processes that involve fault failure is ongoing. For instance, fluid pressure pushes faults towards failure through reduction of effective normal stress, but at the same time make the fault more likely to fail in aseismic slip (Das and Zoback, 2011; Scholz 2002). Aseismic slip on faults can trigger seismic slip further away along the same fault, and this kind of more complex interaction may make spatial interpretation of induced seismicity more difficult.	c) consider—could add to the timeliness of completion	**Heather Savage** *Academic Laboratory*	
1. Introduction Page 1 There are now earthquakes in Kansas, so this statement should be revised or removed.	Clarify context	**Heather Savage** *Academic Laboratory*	
5.4 Injection Induced-Seismicity Faults of Concern (cont) 16. Another general concern that I have is that I think there is way too much emphasis in the report about basement faults. Although many seismically active faults occur within basement rocks, this is not a prerequisite. Because fluid pumping generally occurs within sedimentary sequences, which also have many faults, it is reasonable to assume that either seismic or aseismic processes may begin where the fluid pressures are highest in the sedimentary rocks (i.e. nearer to the well). The 2011 Prague, Oklahoma sequence appears to have started within the sedimentary cover, at least a kilometer above the basement. Some aftershock seismicity continued to within ~250 m of one of the disposal wells (Keranen et al. 2013). I think the suggestion in Appendix B that the depth to basement near a well may be considered in terms of choosing an appropriate site is overstated. Furthermore, the report overstates how aseismic the sedimentary strata above the basement may be. As the report points out, carbonates and sandstone behave mostly brittly. Shales do as well (despite what is written in this report), that is why we extract hydrocarbons from shales by inducing fracture. Although it is true that unconsolidated sediments cannot nucleate earthquakes, when sediments are buried several kilometers they lithify and can behave brittly.	Statement, but FOC being revisited	**Heather Savage** *Academic Laboratory*	

Comment	Consensus	Reviewer	Done
2. P. 2 Hydraulic Fracturing It should be noted that the events related to hydraulic fracturing in British Columbia occurred in strata that were very close to basement rock and this is not typically the case with most current hydraulic fracturing operations in the US. As such, these events may be an artifact of the geologic conditions found here and are not generally reflective of conditions found in US based operations.	Look at it	**Ed Steele** *Oil/Gas Industry and Consultant*	
4. P. 5 1. Injection Induced Seismicity Project Objectives It is suggested that the wording of this be changed to – What parameters are most relevant for the assessment of potential injection-induced seismicity? It is believed that this should be considered a risk assessment exercise.	Look at phrasing, No to risk assessment, see other discussion	**Ed Steele** *Oil/Gas Industry and Consultant*	
6. P. 6 Background It might also be useful to consider such factors as poroelastic stresses and glacial isostatic adjustment in relevant areas. It needs to be recognized that while surface seismic surveys can be helpful, these cannot always locate faults owing to their size and orientation to the seismic survey. There should also be some recognition that the size of a fault may also be an important consideration. Small faults are unlikely to be contributors to strong surface shaking.	TMI for practical approach Last part a true statement, already covered -- Verify	**Ed Steele** *Oil/Gas Industry and Consultant*	
10. P. 20 Common Characteristics and Observations a) Third bullet - This statement could be more precise by stating "basement rock faults" rather than just basement rocks. b) Another bullet could also be added about the lack of a sealing layer between the injection zone and the basement faults.	Clarify text B is more a function of fault seal--covered	**Ed Steele** *Oil/Gas Industry and Consultant*	
12. P. 22 Decision Model Again, significant changes in ground water levels might also be considered.	Verify in geosci discussion	**Ed Steele** *Oil/Gas Industry and Consultant*	
17. P. 29 Management Approach First bullet – This is a very open-ended statement and leaves its interpretation open to question which can result in the second guessing of Directors later on. It is suggested that this statement could be better clarified.	Look at it	**Ed Steele** *Oil/Gas Industry and Consultant*	
19. P. 30 Report Findings a) Fourth bullet – It needs to be recognized that while a petroleum engineering approach can provide useful information, such approaches can be very time consuming and that there are various factors that can impact the accuracy of the outcomes from such. b) Sixth bullet – It is suggested that the wording here be modified to include the word "possible" between the and correlation. As stated, this reads as a definitive case which it is not.	a) is most practical and can be considerable faster than any other method b) agree	**Ed Steele** *Oil/Gas Industry and Consultant*	

Executive Summary Comments

Comment	Consensus	Reviewer	Done
1. Pg ES-1, prgh 3, ln 9 The statement that "EPA is unaware of any USDW contamination resulting from seismic events related to injection-induced seismicity" begs the question as to why produce the document as a UIC document if "no foul" has ever been committed within the jurisdictional boundaries of the UIC regulations whose sole purpose is to protect underground sources of drinking water as stated on pg 1, prgh 1, ln 1.	It's a protective program as opposed to a reactive program- maybe we want to add a sentence about that? Maybe responding with something like this: "The Safe Drinking Water Act requires EPA to establish requirements that will prevent underground injection wells from contaminating underground sources of drinking water. Because seismic events from injection have the potential to cause endangerment of underground sources of drinking water, the UIC program director should be aware of that potential and be prepared with response options should something occur."	**Jeff Bull** *Oil/Gas Industry*	
5. Pg ES-2, prgh 2, footnote 5: The definition of faults of concern needs to be more specific with regard to "significant earthquake" (see Variety and Validity of Approaches – comment 2). The definition also needs to include an expansion of the term "optimally orientated" to include a fault whose orientation is such that the direction of the principal insitu stress is at a 30-50 degree angle to the fault plane. The definition also needs to include a statement that the fault must be critically stressed meaning that there is sufficient stored energy (stress) that should the fault slip, it would generate a seismic event of sufficient magnitude to be detected.	We should likely point to variability in regional geology as the need to stay less prescriptive. Good in doc, regional geo issue (move to main body—also listed there)	**Jeff Bull** *Oil/Gas Industry*	

Comment	Consensus	Reviewer	Done
7. Pg ES-2, prgh 2, ln 9: "The basic assumption that an accurate history of seismic monitoring in the region of the injection well exists" is flawed. To get the best available seismic history one is going to want to look as far back in history as one can go. At best this is 100 years starting with having to rely on individual people reporting felt events, which was not a reliable reporting process. Active monitoring has only taken place within the last 50-75 years and was located primarily in California and not in the historic oil & gas states of TX, OK, CO, WY, NM. Seismometer coverage within the primary oil and gas states improved when the National Array moved into a state; but then the array moved out within 18-24 months. Some of the states chose to keep some seismometers to bolster their ability to detect seismic events from the array while some did not. So one needs to understand the origin and coverage of the historic data and the fact that the accuracy of the historic data has large error horizontal and vertical ellipses that limits the investigators ability to zero in on potential area of concern around a location suspect of induced seismicity.	Comment, covered in appendix Check context	**Jeff Bull** *Oil/Gas Industry*	
5.6 Errors in Scientific Descriptions 1. The section labeled "Geologic Stress Considerations," page 6, says that "…a principle (sic) stress direction exists…" and goes on to talk about the orientation of faults with respect to the "…the principal stress direction." This section is an erroneous condensation of parts of Appendix M, which describes "…three principal stresses that are oriented perpendicular to one another." In fact it is the orientation of faults with respect to the orientation of the three principal stresses that is important. This concept is not accurately stated on page 6.	Move to body main doc section This could be an easy "fix" to the text. (move to main body—also listed there)	**Robin McGuire** *Consultant*	
2. Seismologists do not write about "low magnitude earthquakes…" (see page ES-1 and elsewhere throughout the Report). "Low" is a descriptor of elevation, altitude, or level, not size. The correct description is "small magnitude earthquake."	An easy "fix".	**Robin McGuire** *Consultant*	

Comment	Consensus	Reviewer	Done
3. The term "fault of concern" is used repeatedly (see footnote, page 2, and Glossary), and is defined as "a fault optimally oriented for movement …" Faults do not have to be optimally oriented with respect to the stress field, to generate an earthquake. For an example, see Appendix E, "North Texas Area Lessons Learned," page E-19, bullet 1, where optimal orientation is described as north-south, but regional faults are predominantly oriented northeast to southwest. I would change the definition to "a fault oriented conducive to movement …"	Add lead intro to geoscience on exceptions to the generalized statements An easy "fix".	**Robin McGuire** *Consultant*	
5.2 Previous Studies (first few) In several places the report makes the statement "Evaluation of induced seismicity is not new to the UIC program" (e.g., page ES-2, par. 1). This statement is certainly true but it should be properly documented, and expanded to acknowledge the earlier reports specifically prepared for EPA that discuss this topic of injection induced seismicity and introduced criteria the UIC Director may use to help minimize and manage the potential of induced seismicity related to deep injection well activities [Wesson and Nicholson, 1987; Nicholson and Wesson, 1990]. The reference for Nicholson and Wesson [1990] is briefly mentioned in the report, but not as a report specifically to EPA that also provides the first set of criteria for minimizing the potential for injection induced seismicity. In fact, the complete, correct citation for these two publications are: • Wesson, R.L. and C. Nicholson, Earthquake hazard associated with deep well injection: A report to the U.S. Environmental Protection Agency, U.S. Geological Survey Open-file Report 87-331, 108 pp. (1987). • Nicholson, C. and R.L. Wesson, Earthquake Hazard Associated With Deep Well Injection—A Report to the U.S. Environmental Protection Agency, U.S. Geological Survey Bulletin 1951, 74 pp. plus plate (1990).	Verify how cited and intro response on use First reference is not in the list of citations. Second one is. (Citations are ones actually used in write-up, biblio is more comprehensive. The initial draft was left off, assuming the later document was the approved version.)	**Craig Nicholson** *Academia*	

Comment	Consensus	Reviewer	Done
A possible solution to properly acknowledge this previous work that bears directly on the purpose and intent this report is to expand the sentence (page ES-2, par. 1) to say something like: Evaluation of induced seismicity is not new to the UIC program and in fact, over 25 years ago, EPA Office of Drinking Water commissioned a study by the USGS on the earthquake hazard associated with deep well injection [Wesson and Nicholson, 1987; Nicholson and Wesson, 1990]. This previous work established the first set of criteria for site selection, well drilling and completion, as well as for well operation and monitoring to help minimize and manage the potential for injection induced seismicity. Many of these same criteria and practical approaches are also utilized in this newer, updated UIC report.	AA, consider suggestion This is related to Mr. Nicholson's first point.	**Craig Nicholson** *Academia*	
3. Page ES-3, Executive Summary Suggest restating the sentence "with useful practical tools for managing and minimizing injection-induced seismicity are recommended" to "…managing and minimizing significant injection induced seismicity" to align with the report recommendation that hazards are from faults of concern and significant injection induced seismicity. Non-hazardous levels of seismicity (or micro-seismicity) may be present.	Verify I injection induced seismicity already defined as significant, for use in this document Easy "fix"	**Kris Nygaard** *Oil/Gas Industry*	
There are probably more than 10 wells in the United States that fall into the "suspect" category, especially since less clear-cut cases often have several well nearby that could be the cause of recent seismicity.	Depends on writer's bias this may be true with more seismic monitoring now – maybe we should reword to stress modern increased awareness levels or it could also work to be less specific about the # of incidents There is also a clarification on the period covered by the paper. Do we need to acknowledge all of the OK events when they postdated the Ohio event, which was the last one we worked with.	**Heather Savage** *Academic Laboratory*	

Comment	Consensus	Reviewer	Done
1. P. ES-2 The statement "A basic assumption is that an accurate history of seismic monitoring in the region of the injection well exists" is at variance with other statements in the text. This statement should be qualified to note that the accuracy of such monitoring depends on the robustness of the seismic network for any given area and with consideration for how long such a network has been in place. As is well stated elsewhere in the document, both epicenter and hypocenter location determinations will be dependent upon the number of monitoring locations.	Might be worth adding a clarifying sentence here also	**Ed Steele** *Oil/Gas Industry and Consultant*	
2. P. ES-3 It is recommended that the last sentence on this page be modified to include hydrogeology, seismology, petrophysics, and geomechanics as part of a multi-disciplinary approach.	we're ok with our current wording Don't have the sentence in front of me, but what about "include hydrogeology, seismology, and other scientific fields of study as part of a multi-disciplinary approach."	**Ed Steele** *Oil/Gas Industry and Consultant*	